

Heat to electricity thermoacoustic-magnetohydrodynamic conversion

A. A. Castrejón-Pita[‡] and G. Huelsz

Centro de Investigación en Energía, Universidad Nacional Autónoma de México,
Ap. P. 34, 62580, Temixco Morelos, México

12/10/2006

Abstract

In this work, a new concept for the conversion of heat into electricity is presented. The conversion is based on the combined effects of a thermoacoustic prime mover coupled with a magnetohydrodynamic generator, using different working fluids in each process. The results of preliminary experiments are also presented.

1 Introduction

¹ Heat to electricity transducers are devices of enormous importance in modern society. Most of them use an intermediate step in which thermal energy is converted into some kind of mechanical energy that can be used to generate electricity. Since the beginning of the development of thermoacoustic engines, there have been some proposals for the use of thermoacoustic prime movers coupled with magnetohydrodynamic transducers to generate electricity. These devices can potentially be used as solar energy to electricity converters and, depending on their efficiency and cost, could be an alternative to photovoltaic cells. Also, due to its simplicity and the absence of moving rigid components, thermoacoustic electricity generation can conveniently be used in space applications.

A thermoacoustic prime mover is a device that converts thermal energy into mechanical energy in the form of acoustic waves. The thermoacoustic effect arises due to the thermodynamic interaction between a compressible fluid and solid surfaces that possesses a suitable axial temperature gradient. Depending on the form of the resonator and the location of the temperature gradient, the thermoacoustic prime mover can generate a standing-wave or a traveling-wave. An extensive review of the thermoacoustic principles in the context of engines can be found in [1]. A magnetohydrodynamic (MHD) transducer uses the motion of an electrically conducting fluid under an applied magnetic field to convert the fluid mechanical energy into electricity. The relative motion of the fluid and the applied field induces an electric current in the direction transversal to both the fluid motion and the field, that can be extracted through electrodes suitably located in the device. MHD electrical generators have been widely investigated and many interesting designs have been proposed [2, 3].

Previously, two alternative ways to use thermoacoustic oscillations to produce alternating electrical current have been proposed. In the first one, the device is composed by a thermoacoustic prime mover and a magnetohydrodynamic transducer ([4] and [5]). It uses an electrically conducting liquid as the working fluid for both energy conversion processes. The disadvantage of this type of heat to electricity transducer is that high pressures (of the order of 150 atmospheres) for the liquid inside the resonator are needed

[‡] Present address: Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom.

in order to generate the acoustic oscillations. In the second alternative, the oscillatory pressure wave in a gas generated by the thermoacoustic effect is used to drive an electrically conducting piston in the presence of a magnetic field to generate electric power [6].

In this paper, a third alternative for the use of thermoacoustic oscillations to produce electricity is presented.

2 Description of the concept

The alternative proposed in this work is similar to the first one, it uses a thermoacoustic prime mover and a magnetohydrodynamic transducer. The originality of this new concept consists in the use of two working fluids separated by gravity, a gas for the thermoacoustic prime mover and an electrically conducting liquid for the magnetohydrodynamic transducer.

The heat to electricity transducer is composed of a thermoacoustic prime mover, a U-tube partially filled with the liquid and a MHD Faraday generator. The thermoacoustic prime mover and the liquid in U-tube form a coupled oscillators system. In the bottom of the U-tube a conventional MHD Faraday generator is located. The oscillatory motion of the electrically conducting liquid under the magnetic field generates an alternate electric potential difference at the electrodes. In this way, it is possible to extract electrical power from the generator when a load is connected to the electrodes through an external circuit.

3 Preliminary experiments

To specify the concept a simple device is constructed. The thermoacoustic prime mover resonator is a Helmholtz one[7], filled with air. The Helmholtz resonator is formed by a spherical cavity and a straight tube which is connected to an U-shaped tube. The lowermost section of the sphere of the resonator is surrounded by an electrical resistance that generates a temperature axial gradient on the tube near their upper part. When the imposed temperature gradient is appropriate, a thermoacoustic wave is generated in the air inside the Helmholtz resonator which, in turn,

drives an oscillatory motion of an electrolyte inside the U-tube. In the bottom of the U-tube a conventional MHD Faraday generator is located. It consists of a duct of square cross-section where two permanent magnets are placed in opposite electrically insulated walls in such a way that the resulting magnetic field is perpendicular to the oscillatory motion of the electrolyte. Two electrodes are located at the other pair of walls in the region where the magnetic field is more intense. The geometry of the transducer is shown in figure (1). The oscillatory motion of the electrolyte under the magnetic field generates an alternate electric potential difference at the electrodes. In this way, it is possible to extract electrical power from the generator when a load is connected to the electrodes through an external circuit.

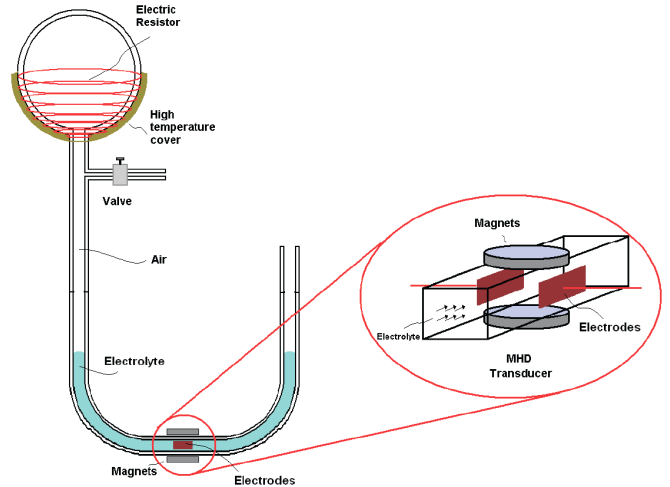


Figure 1: Sketch of the heat to electricity thermoacoustic-MHD transducer.

The sphere and the tubes used in the experiments (except for the lower part of the U-tube) are made of soda-lime glass with a wall thickness of 1.5 mm. The diameter of the sphere is 38 mm and the internal diameter of the tubes is 5 mm. The poor thermal conductivity of the glass helps to generate a large enough temperature axial gradient in the tube near the heated zone. The temperature of the external wall of the heated zone (T_h) is monitored with a thermocouple. The lower part of the U-tube is a plastic

duct of external rectangular cross section of 8.00 mm \times 7.76 mm and a wall thickness of 0.7 mm. The total length of the tubes $L = L_h + L_u + L_o$ is 35 cm, where L_h is the length of a thermoacoustic tube, L_u is the length of the liquid column in the U-tube, and L_o is the length of the open tube filled with air. The electrolyte used for this preliminary test is a saturated sodium bicarbonate aqueous solution (electrical conductivity of $6.4\Omega^{-1}m^{-1}$). Neodymium magnets of circular cylinder shape, 19 mm in diameter, 10 mm height, with a maximum magnetic field strength of 0.3 Tesla at the center of the circular face, were used. The electrodes are made of copper plates of 6 mm long and 4 mm high placed on lateral walls inside the tube. The distance between electrodes (d) is 6 mm. Thin wires welded to the electrodes go through small holes drilled on the plastic duct wall so that an external circuit can be connected. The potential difference between the two electrodes was real-time measured with an oscilloscope and digitalized by an HP 3709 data acquisition system. The axial oscillatory velocity of the electrolyte, at the center of one of the vertical tubes, was measured using a DANTEC laser Doppler anemometer (LDA). The magnitude of the frequency spectrum was obtained using Lomb normalized periodograms [8].

With a fixed temperature $T_h = 350^\circ\text{C}$, the length of the liquid column was varied to obtain the maximum liquid column oscillation. LDA measurements confirmed that maximum oscillation, obtained for a $L_h = 14$ cm, and $l_u = 11$ cm, was achieved when the oscillation frequency 5.3 ± 0.1 Hz is close to the thermoacoustic optimum frequency ~ 7 Hz, given by the diameter of the tube [1]. The experimental results reported in the following are obtained for this lengths relation, all this experiments were made for open circuit conditions.

As an example of the LDA measurement results, the axial oscillatory velocity of the electrolyte (u) and its frequency spectrum and $T_h = 510^\circ\text{C}$, $T_c = 30^\circ\text{C}$ conditions are shown in figures 2 and 3. From them, the amplitude of the oscillatory velocity and the frequency are obtained, being $u_a = 0.848 \pm 0.005$ m/s and $f_0 = 5.6 \pm 0.1$ Hz respectively, the second frequency is $3f_0 = 16.8 \pm 0.1$ Hz and its magnitude is less than 20% of the magnitude of the fundamental

frequency.

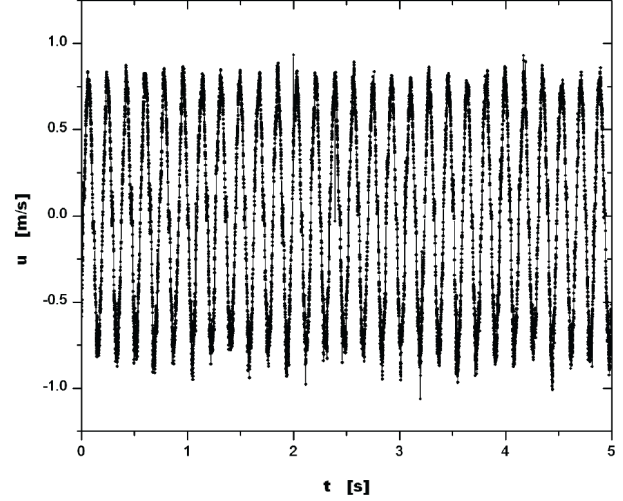


Figure 2: Axial oscillatory velocity of the electrolyte (u), for $T_h = 510^\circ\text{C}$.

The amplitude of the axial velocity (u_a) of the electrolyte as a function of the temperature T_h presents hysteresis, as shown in figure 4. The upper branch is a monotonously increasing function of the temperature. The frequency of oscillation lightly depends on T_h , from 5.2 ± 0.1 Hz for $T_h = 180^\circ\text{C}$ to 5.6 ± 0.1 Hz for $T_h = 510^\circ\text{C}$.

In figure 5 the root mean square voltage (V_{rms}) produced by the device as a function of the root mean square velocity of the electrolyte (u_{rms}) is shown; the symbols correspond to experimental results and the dashed line corresponds to a linear fit $V_{rms} = 0.00006 + 0.0020u_{rms}$. The theoretical curve $V_{rms} = Bdu_{rms} = 0.0018u_{rms}$ is presented as a solid line [9].

It is possible to extract electrical power from the generator when a load is connected to the electrodes through an external circuit. Since the voltage generated by this simple device is so small, measurements of the extracted electrical power as function of the external load were not performed. A more sophisticated design using two thermoacoustic prime movers connected through the U-tube and optimized fluids and geometry is expected to produce a much higher

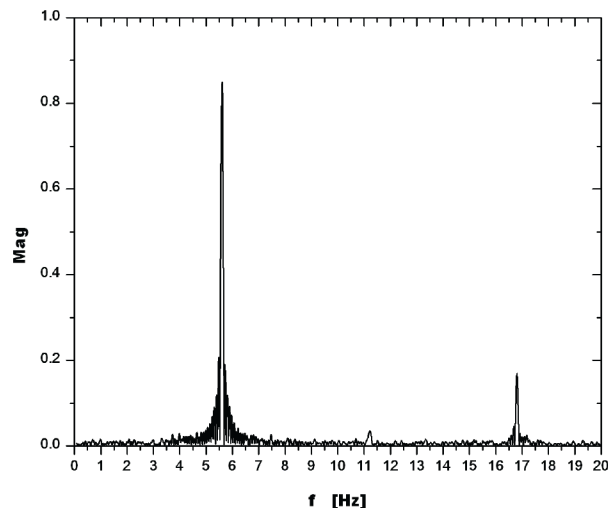


Figure 3: Frequency spectrum of the axial oscillatory velocity of the electrolyte (u), for $Th = 510^\circ\text{C}$.

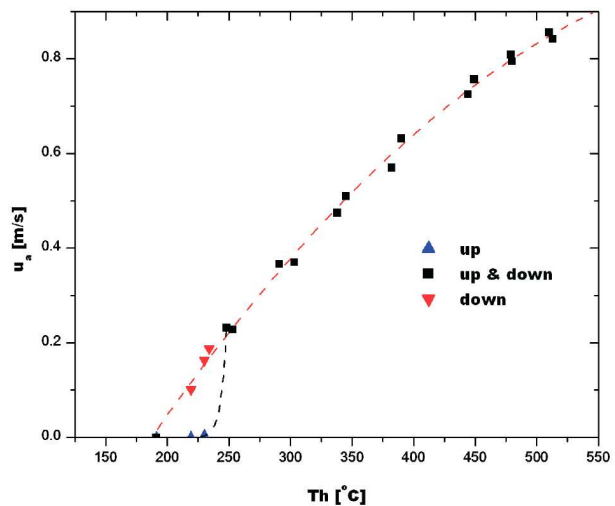


Figure 4: Amplitude of the axial velocity (u_a) of the electrolyte as a function of the temperature Th .

voltage and consequently, a better overall efficiency.

4 Conclusions

A new concept of a heat to electrical power transducer based on the concurrent action of a thermoacoustically produced compressible wave and a magnetohydrodynamic transducer, that uses two fluids, a gas for the thermoacoustic prime mover and an electrical conductor liquid for the magnetohydrodynamic transducer is presented. In principle, this device can be used to generate electricity from a heat source as long as the system is in the presence of gravity or a centrifugal force. The concept is demonstrated with a simple device, but a more sophisticated design using two thermoacoustic prime movers connected through the U-tube and optimized fluids and geometry, is expected to have a much higher overall efficiency. Specially, if the natural frequency of the thermoacoustic prime movers and of the liquid column are commensurable, ideally the same, the oscillation frequency of the coupled system would be optimized. This optimal coupling would lead to larger oscillation amplitudes, and therefore, the efficiency of the device would in-

crease.

5 ACKNOWLEDGEMENTS

This work was supported by the CONACyT U41347-F project. The authors wish to thank Eduardo Ramos and Sergio Cuevas for their comments, and Margarita Miranda and Guillermo Hernández for their technical support.

References

- [1] Swift G.W. 2002 *Thermoacoustics: A unifying perspective for some engines and refrigerators* (Acoustical Society of America, Sewickley, PA).
- [2] Branover H. and Unger Y. 1993 Metallurgical technologies, energy conversion, and magnetohydrodynamic flows. Progress in Astronautics and Aeronautics Volume 148.
- [3] Branover H. and Unger Y. 1998 Progress in fluid flow research: turbulence and applied MHD. Progress in Astronautics and Aeronautics Volume 182.

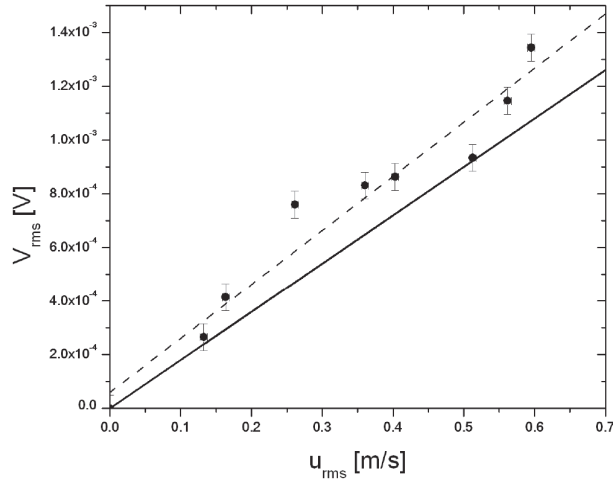


Figure 5: Root mean square voltage (V_{rms}) in open circuit conditions produced by the device as a function of the root mean square velocity of the electrolyte (u_{rms}). Symbols are experimental results, the dashed line is the linear fit to them, the solid line represents theoretical prediction.

- [4] Swift G.W. 1988 A liquid-metal magnetohydrodynamic acoustic transducer, J. Acoust. Soc. Am. **83**, 350-361.
- [5] Ovando, G., Huelsz, G., Ramos, E., and Cuevas, S. 2005 Effect of a magnetic field on the linear stability of a thermoacoustic oscillation. J. Non Equilibrium Thermodynamics, **30**, No 2, 137-149.
- [6] Backhaus S., Tward E. and Petach M. 2004 Traveling-wave thermoacoustic electric generator Appl. Phys. Lett. **85**, No 6, 1085-1087.
- [7] Temkin S. 2001 *Elements of acoustics* (Acoustical Society of America, American Institute of Physics, Sewickley, PA).
- [8] Press W H, Teukolsky S A, Vetterling W T, and Flannery B P, 2002 *Numerical Recipes in C++* (Cambridge University Press, New York).
- [9] Rosa R.J. 1987 *Magnetohydrodynamic energy conversion* (Hemisphere, New York).